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August 1980

PARAMETRIC ANALYSIS OF ENERGY CONSUMPTION IN ARMY BUILDINGS BY THE BUILDING LOADS ANALYSIS AND SYSTEM THERMODYNAMICS (BLAST) COMPUTER PROGRAM

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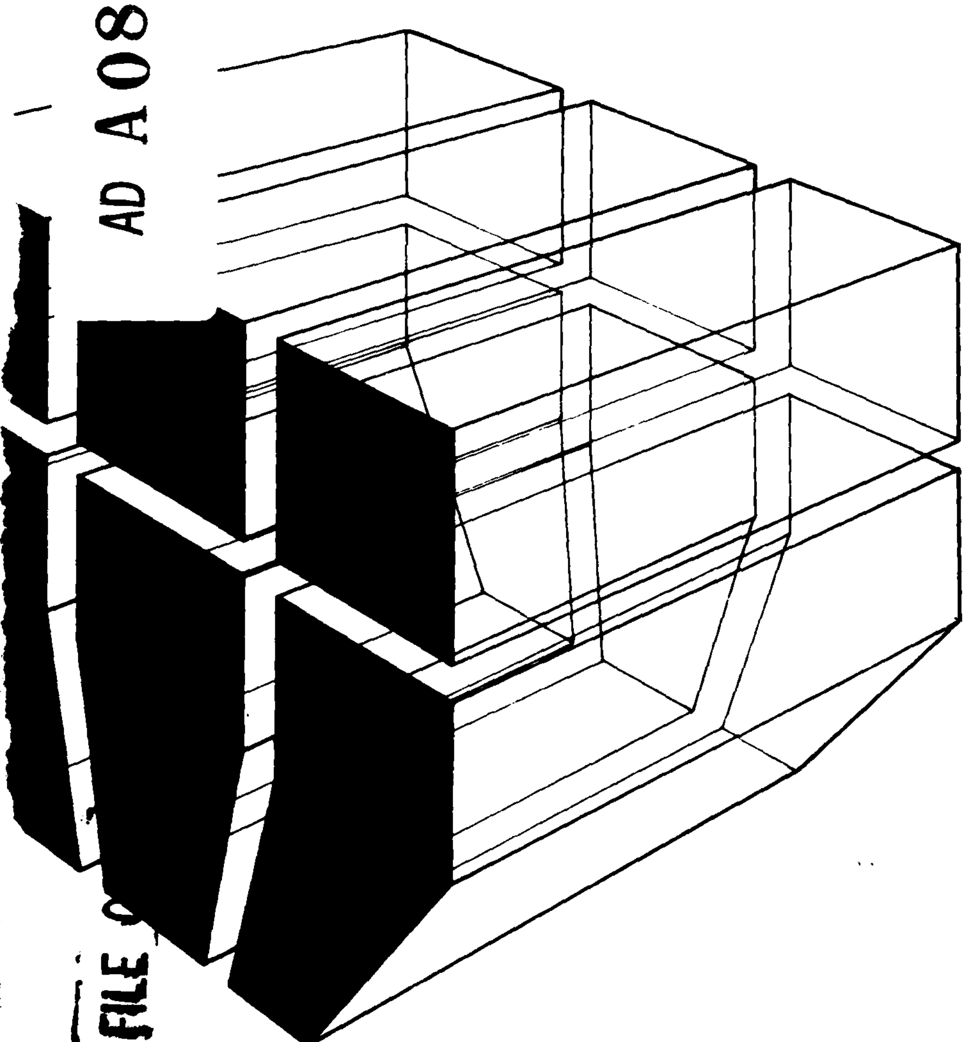

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This report describes the effects varying architectural, construction, and mechanical system features have on the energy consumption of three Army buildings: a barracks, an administration building, and a dental clinic. The three buildings were simulated for five climatological regions centered at Washington, DC; Charleston, SC; Los Angeles, CA; Columbia, MO; and Fort Worth, TX. Energy consumption simulations were done by the Building Loads Analysis and System Thermodynamics (BLAST) computer program.

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The report shows the percentage difference in annual heating and cooling energy use for three buildings and five locations when variations from the as-built insulation levels, orientation, window areas, window types, infiltration levels, mechanical system, and system control strategies are used.

It was concluded that insulation levels, window size and type, and infiltration/ventilation rates are the most important architectural and construction features affecting the degree of energy consumption, and that proper selection of mechanical system type and system control strategies can reduce annual energy consumption by up to 50 percent.

FOREWORD

This work was performed for the Directorate of Military Programs, Office of the Chief of Engineers (OCE), under Project 4A762731AT41, "Design, Construction, and Operation and Maintenance Technology for Military Facilities"; Technical Area 06, "Energy Systems"; Work Unit 023, "Effect of Design Criteria on Energy Consumption in Buildings." The applicable QCR is 3.02.002. Mr. N. M. Newman, DAEN-MPE-B, was the OCE Technical Monitor. The work was performed by the Energy Systems Division (ES) of the U.S. Army Construction Engineering Research Laboratory (CERL). Mr. R. G. Donaghy is Chief of ES.

Appreciation is expressed to the following CERL personnel who helped with this study: Mr. Douglas Hittle, for assistance in describing the mechanical systems and control strategies; Mr. Bill Dolan for assistance in describing the buildings and computing the building parameter values; and Mr. Andrew Mech for assistance in data analysis.

COL Louis J. Circeo is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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1 INTRODUCTION

Background

The Army must have functional, durable, and energy-efficient facilities. In the past, architectural features, construction materials, and heating, ventilating, and air-conditioning (HVAC) equipment were usually selected for their minimum initial cost rather than their energy conservation attributes. But today's high energy costs now demand that consideration be given to such energy consumption variables as window area, orientation, and insulation level during the facility design phase. However, the quantitative effects of component variables on overall building energy consumption in various climatic regions is not known, making it difficult to do a cost or energy analysis of a facility. Although the energy consumed by a facility is a function of many component variables, tradeoffs can be made among them without changing the total measurement of energy consumption.[1] Overemphasizing the performance of one or a few design features is not always the most cost-effective way of conserving energy. Therefore, the Army needs a set of procedures which allows engineer divisions and districts some latitude to manipulate building design features during design, yet control and predict the total energy consumption of the new facility.[2]

Before tradeoffs can be made among various options, the features that affect energy consumption must be analyzed on a quantitative basis. Accurate quantitative analysis of energy consumption in buildings was once extremely tedious and time consuming, since complex calculations had to be performed by hand. But the development of sophisticated building energy consumption computer simulation programs which perform detailed building thermal loads analyses and system simulations has made efficient and inexpensive parametric analysis of the effects of construction and design decisions on building energy consumption both possible and practical.

Since building energy consumption simulation programs can help Corps of Engineers divisions and districts evaluate the proper energy conservation options to be applied to new construction and major retrofit projects, the U.S. Army Construction Engineering Research Laboratory (CERL), adapting the best features of several available simulation programs, developed the Building Loads Analysis and System Thermodynamics (BLAST) computer program to meet the needs of Army users.[3]

Objective

The objective of this study was to use the BLAST computer program to describe the quantitative effects changes to building construction, materials, orientation, and HVAC systems have on three Army buildings in five different climatic regions.

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[1] *Optimization of Energy Usage in Military Facilities* (Phase I) TR-75-22 (Air Force Civil Engineering Center [AFCEC], October 1975).

[2] *Energy Consumption Tradeoff Procedures for Facility Design Evaluation*, Qualitative Construction Requirements, QCR 3.02.002 (12 April 1977).

[3] D. C. Hittle, *The Building Loads Analysis and System Thermodynamics (BLAST) Program, Version 2.0, Users Manual, Volumes I and II*, Technical Report (TR) E-153/ADA072272 and ADA722730; and E. Sowell, *The Building Loads Analysis and System Thermodynamics (BLAST) Program Input Booklet*, TR E-154/ADA072435 (U.S. Army Construction Engineering Research Laboratory [CERL], June 1979).

Approach

Three building types were selected for energy consumption analysis and the construction options and building system types to be studied and climatic regions to be simulated in the analysis were chosen. The selected buildings were coded for input to the BLAST computer program; parametric analyses of construction options and system types in each climatic region were then performed and the results analyzed.

2 EXPERIMENTAL SETUP

The major energy conservation items listed in the Department of Defense (DOD) *Construction Criteria Manual* are insulation level, system control, orientation, window area, and window glazing type.[4]

The building types selected for the BLAST simulations described in this report were (1) the modern Army (BB&A design) 141-man enlisted barracks, (2) an administration building of the type normally constructed as part of the modern Army barracks complex, and (3) a 28-chair dental clinic. These buildings included multistory and single-story structures with different mechanical system types. These buildings were considered representative of Army buildings designed in the 1970s and currently being built at Army installations. Therefore, BLAST simulations were designed to vary orientation; percent glass; glazing type; wall, roof, and floor "U" values; infiltration; mechanical system control schemes; and different heating or cooling system distribution types in three representative Army buildings.

The climatic data for the BLAST simulations were obtained from weather tapes of five climatic regions centered at Los Angeles, CA; Washington, DC; Columbia, MO; Fort Worth, TX; and Charleston, SC. These cities were selected because they provided a wide range of heating and cooling loads and included areas of the country having a large number of Army installations.

Simulation Method

The buildings were coded from the as-built drawings for input into the BLAST program. An initial computer run was then made to determine the present "baseline case" heating and cooling loads for the buildings. Next, a number of simulation runs were made to analyze the differences in loads caused by variations in the building construction and system parameters and these results were analyzed. The appendix briefly describes the BLAST program capabilities and features used in the analysis.

Building Selection

Barracks

The type of barracks building selected for the BLAST computer program analyses is currently in the Army inventory and is programmed for future construction throughout the Army. It is a four-module, three-story structure designed to house 141 persons. Each module contains 1780 sq ft (23.8 m^2) per floor. Each set of two modules is connected by a breezeway. The total wall area of the building is 19,925 sq ft (1852 m^2), of which 12 percent (2398 sq ft [223 m^2]) is glass. The walls are constructed of 4-in. (102-mm) face brick, with a 2-in. (51 mm) air space and 8-in. (204-mm) concrete blocks with filled cores. The roof is a five-ply built-up roof on a concrete deck with 2 in. (51 mm) of insulation. Individual fan/coil units located in each room, the corridor, and the lounge provide heating and cooling. Hot and chilled water are supplied from a remotely located central plant. A water-to-water heat exchanger produces both low-temperature water for the fan/coil units and domestic hot water.

Only two of the four modules were modeled for this study, since the module sets on either side of the breezeway are identical. Therefore, the simulated annual energy consumption figures shown in Chapter 3 are *one-half* of the complete energy consumption. Figure 1 shows a top view of the two modules for the barracks building.

Administration Building

The administration building is a two-battalion headquarters and classroom facility that has storage, clerical, conference, and classroom areas housed in a single-story brick structure. The classrooms are 40 by 24 ft (12 by 7.2 m), with a projection room at one end and a stage at the other. Each battalion

[4] *DOD Construction Criteria Manual*, DOD 4270.1-M (Department of Defense [DOD], October 1, 1972).

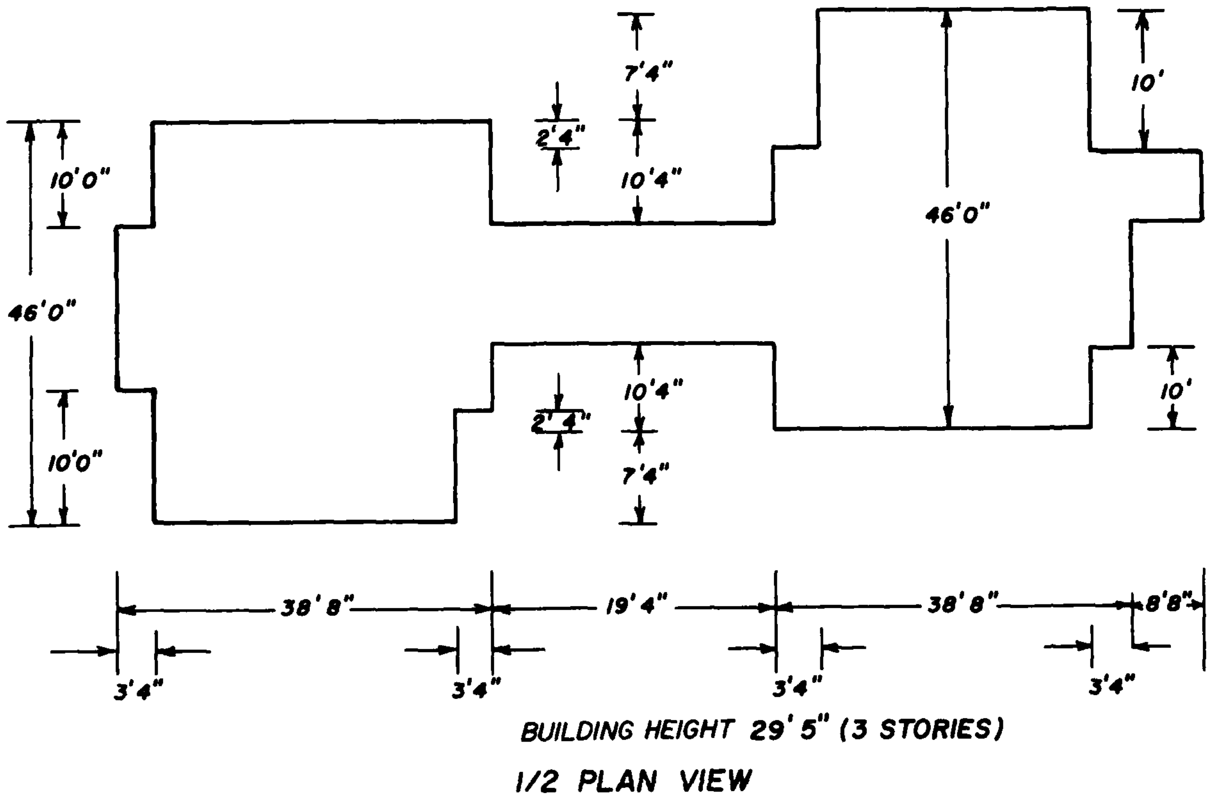

Figure 1. Barracks building.

has a clerical area with two adjoining offices, a conference room, and several rooms used for storage and supply issue. The total floor space is 17,636 sq ft (1587 m^2); window area is 466 sq ft (42 m^2).

The wall construction consists of 4-in. (102-mm) face brick, a 2-in. (51 mm) air space, and filled-core, 8-in. (204-mm) concrete block. The roof construction is five-ply built-up roofing on a steel deck, with an air space and a drop ceiling of acoustical tile covered with 2-in. (51-mm) fiberglass insulation. The floor is a slab-on-grade, except on two corners, where a partial basement houses a rifle range and small-arms vault. (For the energy consumption simulation model, this basement area was ignored; since it is used intermittently, it is served by a separate air-handling system and its effects on envelope heat transfer are not appreciable.) The overall heat transfer coefficients for the wall and ceiling/roof are 0.236 and 0.093 Btu/hr-sq ft-$^{\circ}$F (1.34 and 0.53 W/$^{\circ}$K-m^2), respectively. The administration portion of building is heated and cooled by a multizone unit; the storage areas are served by unit heaters. Hot and chilled water are supplied to the building from a remote central plant. Figure 2 is a single-line drawing of the administration building.

Dental Clinic

The dental clinic is a single-story structure with a floor area of 9384 sq ft (845 m^2) and a window area of 216 sq ft (19 m^2). The clinic's usable space includes 18 operating rooms, three offices, two X-ray rooms, one lab, a machine shop, men's and women's locker rooms, a records room, and a conference room. A 21 by 31 ft (6.3 by 9.3 m) open enclosure housing mechanical and electrical equipment is appended to one corner of the clinic. The intended occupany level during normal weekday operation is 63 people.

The wall construction consists of 4-in. (102-mm) face brick, a 2-in. (51-mm) air space, and 4-in. (102-mm) heavyweight concrete block covered with a 3/4-in. (19-mm) plasterboard interior finish. The ceiling and roof construction consists of a built-up roof over rigid underlayment, a metal deck, a 2-ft (0.6-m) air space, and a drop ceiling with 3 in. (76 mm) of fiberglass insulation. The floor (over a crawl space) is poured heavyweight concrete 2 in. (51 mm) thick with 1-in. (25-mm) insulation bonded to the bottom. Overall heat transfer coefficients for the wall, ceiling/roof, and floor are 0.294, 0.012, and 0.174 Btu/hr-sq ft-$^{\circ}$F (1.67, 0.07, and 0.99 W/$^{\circ}$K-m^2), respectively.

The clinic's environment is maintained by a multizone air-handling unit served by its own boiler and chiller. The building was modeled with 30 percent outside air as stipulated on the as-built drawings. Figure 3 is a single-line drawing of the dental clinic.

Climatic Regions

Five climatic regions within the United States were selected to study variances in the buildings' annual heating and cooling loads. A "typical" weather year was selected for each site from National Climatic Center weather tapes; i.e., that year having the smallest annual sum of deviations between monthly mean temperatures and long-term monthly mean temperatures. The typical years chosen for the five sites were: 1955 (Charleston); 1956 (Columbia); 1957 (Washington); 1973 (Los Angeles); and 1975 (Fort Worth).

These climitic selections, while obviously not covering all areas of the United States, represent a sample of different climatological and seasonal variations. The regions also represent areas that include most continental United States (CONUS) Army installations. Table 1 shows annual heating degree days, cooling degree days, annual mean temperatures, and average daily solar radiation for each of the five sites.

Parameter Selection

The energy consumption parameters selected were: (1) structural and architectural features of the building, and (2) mechanical systems and control schemes. Structural energy conservation features were limited to those which could reasonably be applied to each building in a retrofit mode (i.e., no size changes or interior rearrangements of the buildings).

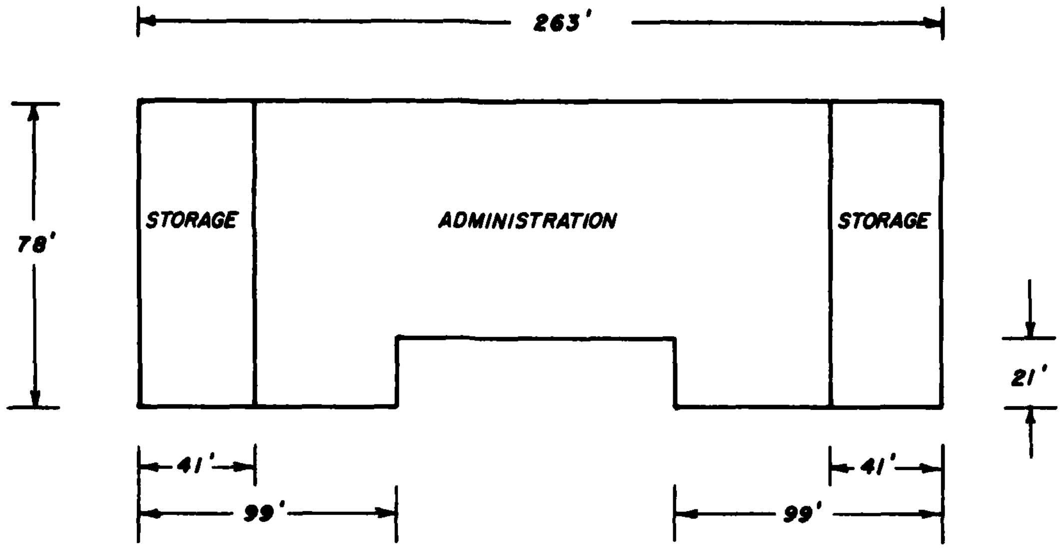

Figure 2. Administration building.

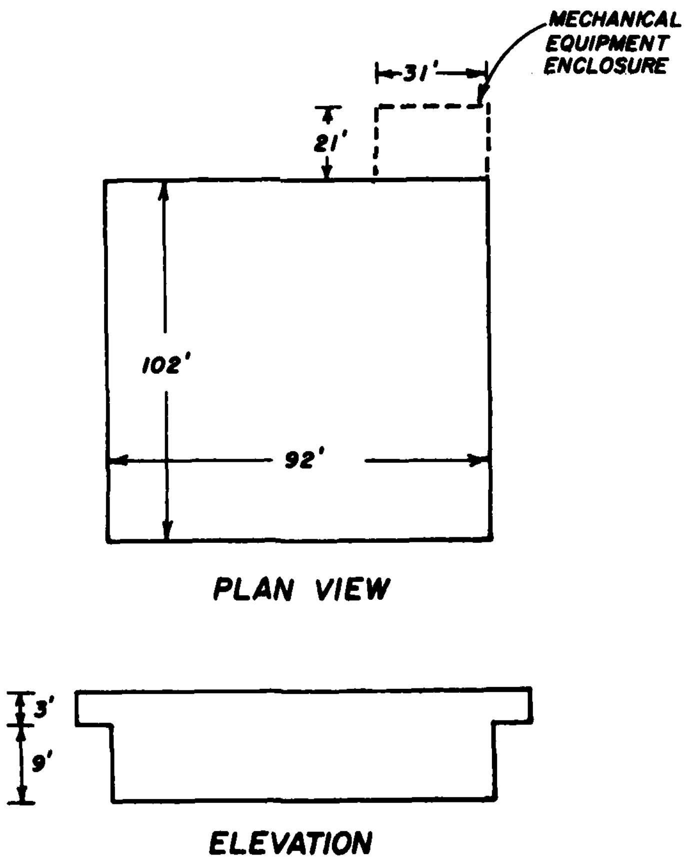

Figure 3. Dental clinic.

Table 1

Weather Tape Summary

Site	Total Heating Degree Days	Total Cooling Degree Days	Annual Mean °F (°C)	Average Daily Langleys (W/m^2)
Washington, DC	4111	1526	57.9 (14.40)	384 (4458)
Charleston, SC	2153	2036	65.7 (18.15)	434 (5036)
Fort Worth, TX	2276	2553	65.7 (18.75)	474 (5496)
Columbia, MO	5141	1240	54.3 (12.4)	382 (4438)
Los Angeles, CA	1517	392	61.9 (16.62)	450 (5226)

The comparisons of the annual energy use related to structural and architectural features were made using the type of air distribution system described on the as-built drawings of the buildings. To ensure consistency between load simulations, the heating and cooling decks were controlled so that they never operated simultaneously; this ensured that the air was never both heated and cooled to achieve the desired space temperature. The loads determined by the BLAST simulation program were based on a desired room space temperature of 68°F (20°C) during the heating season and 78°F (25°C) during the cooling season; the systems were allowed to run intermittently.

Structural and Architectural

The first parameter varied was the buildings' insulation levels. During the simulation runs, wall and roof insulation levels were changed both individually and collectively to obtain overall building "U" values* for the structures (Table 2). In the case of the dental clinic, which had a floor over a crawl space, the floor insulation was also varied. Insulation levels are often initially considered when energy conservation is discussed. In this study, specific changes in "U" values were made to determine the effects of increasing and decreasing the amount of insulation in logical increments for each climatic region. The quantitative effect of the insulation level could then be compared in each region to determine where the greatest effects occur.

The second parameter studied was the rate of infiltration and ventilation, which was varied over a range of zero to twice the infiltration coded for the baseline buildings. (Infiltration and ventilation were taken as one air change per hour for the baseline simulation.) Infiltration/ventilation rates were considered to determine (1) the percentage of a building's total load during both the heating and cooling seasons which is attributable to infiltration/ventilation and (2) the linearity of the simulated infiltration/ventilation load.

The building orientation was also varied. Since the buildings are basically symmetrical, building load determinations were made for a 0-degree main axis (north), a 45-degree main axis, and a 90-degree main axis.

Another parameter selected for variation was window area and type. BLAST simulation runs were made for the barracks and administration buildings for zero window area, twice the window area, and for double-pane instead of single-pane windows. These runs were made to determine the difference in a building's energy consumption resulting from the size and type of windows and to observe the different ratios of heat loss/gain through windows under different climatic conditions.

A final parameter studied was building overhang. The dental clinic building, which has an overhang, was analyzed to determine the effect of removing the overhang.

Table 3 shows a matrix of the structural and architectural simulations made in each building.

Mechanical and Control Systems

For each building type, the "base case" energy consumption for the structural and architectural considerations listed above was based on the type of air distribution system installed in the as-built structure. These systems could not always be compared with other systems because of the way they were operated. Most Army buildings are operated with the heating and cooling systems on or off seasonally. This makes a multizone system operate much like a two-pipe fan/coil system, and subsequently, one-to-one comparisons cannot be made. Therefore, typical systems were defined based on standard systems; these were used for the simulations. Various control strategy options were applied to determine their effects on annual heating and cooling energy consumption.

System simulations in two different climatic regions were run for the dental clinic. The dental clinic simulations were also valid for the administration building, since both buildings have similar load patterns. System simulations were not made for the barracks; however, the two-pipe fan/coil system that is installed in this building and its seasonal operation of the heating and cooling system are considered energy efficient and probably could not be improved.

* Overall heat transfer coefficient.

Table 2

"U" Values for Each Parametric Run

"U" Values	Barracks Walls	Barracks Roof	Barracks Overall	Administration Walls	Administration Roof	Administration Overall	Dental Clinic Walls	Dental Clinic Roof	Dental Clinic Overall
As-built	0.240	0.058	0.260	0.237	0.094	0.164	0.0290	0.081	0.171
Delete filled core of concrete blocks	0.303	0.058	0.295	0.300	0.094	0.181	--	--	--
Add 2 in. (51 mm) of poly-styrene to walls	0.073	0.058	0.171	0.073	0.094	0.121	0.118	0.081	0.140
Delete roof insulation	0.240	0.264	0.333	0.237	0.251	0.272	--	--	--
Add 4 in. (102 mm) of fiber-glass to roof	0.240	0.035	0.252	0.237	0.046	0.131	--	--	--
Delete roof and wall insulation	0.303	0.265	0.367	0.300	0.251	0.289	--	--	--
Add 2 in. (51 mm) of poly-styrene to walls and 4 in. (102 mm) of roof insulation	0.073	0.035	0.163	0.073	0.046	0.088	--	--	--
Delete 1 in. (25 mm) of crawl space insulation	--	--	--	--	--	--	0.118	0.411**	0.266
Add 3 in. (76 mm) of crawl space insulation	--	--	--	--	--	--	0.118	0.068**	0.126

* Overall "U" value includes a summation of the products of the walls, doors, windows, and roof "U" values times their respective areas divided by the total area of walls, doors, windows, and roof.

** Roof "U" value.

Table 3

Structural and Architectural Simulations

Parameter Changes	Barracks Building	Administration Building	Dental Clinic
As-built in field	x	x	x
Remove insulation from walls	x	x	
Remove insulation from roof	x	x	x
Add 2 in. (51 mm) of insulation to walls	x	x	x
Add 4 in. (102 mm) of insulation to roof	x	x	
Remove wall and roof insulation	x	x	
Add 2 in. (51 mm) to walls and 4 in. (102 mm) to roof	x	x	
Zero infiltration/ventilation	x	x	x
Twice the as-built infiltration/ ventilation	x	x	
45-degree orientation	x	x	
90-degree orientation	x	x	
No windows	x	x	
Twice the as-built window area	x	x	
Double-pane windows	x	x	
Remove floor insulation			x
Add floor insulation			x
Remove overhang			x

The first system simulation for the dental clinic used a standard multizone which operated continuously. It had a fixed set-point control for the hot and cold decks (140 and 55°F [60 and 13°C] and used a single throttling range (i.e., full heating at 73°F [23°C] and full cooling at 77°F [25°C]) for controlling the space temperature. This type of system, although not used in the Army, historically typifies how multizone systems were first applied. The system allows heating and cooling to be accomplished simultaneously (this type of operation is sometimes called bucking); the fan operates continously.

The multizone control strategy simulation allowed the system to operate intermittently; i.e., the fan was turned on only when the building required either heating or cooling. The controls on the deck temperatures were set to operate at specified temperatures based on the outside air temperature. This ensured that the hot deck would be at 140°F (60°C) when the outside air temperature was 0°F (-18°C), and at 70°F (21°C) when the outside air temperature was at 70°F (21°C). The cold-deck temperature would be controlled at 55°F (13°C) when the outside air temperature was 95°F (35°C) and at 65°F (18°C) when the outside air temperature was 65°F (18°C) or above.

This multizone control strategy simulation used lower air to coil temperature differentials, thereby eliminating some bucking. The intermittent operation allowed the fan to turn off when the temperature of the space was between 73 and 77°F (23 and 25°C).

The next control strategy simulation used fixed set-point control on the hot and cold decks, but added a night and weekend setback to the space temperature controls. The night and weekend setback allowed the temperature in the space to drop to 60°F (15°C). The heat was on only when the space temperature dropped below 60°F (15°C). The space temperature was allowed to float during periods of nonoccupancy; i.e., there was no cooling when the space was unoccupied.

Using this control strategy, various simulations were run for different hot- and cold-deck controls, the outside-air-controlled decks, and a zone-controlled/deck strategy. (In a zone-controlled deck, the hot- and cold-deck temperatures are controlled by the building zone requiring the most heating or cooling, and the deck temperatures are set to a temperature that will sufficiently meet that load. The upper and lower bounds of the hot- and cold-deck temperatures are different than in the outside-air-controlled strategy, but are adjusted linearly by the controller.)

The control strategy simulation for the multizone system was a temperature economy cycle, in which additional outside air (above the minimum) was introduced when the outside air temperature was below the desired mixed-air temperature. The outside air and return air were then proportioned to maintain the desired mixed-air temperature.

A three-deck multizone system was then simulated. This type of system incorporates an additional deck (free deck) that has no heating or cooling coil. In this system, the air is not heated and cooled simultaneously. For example, if heating is required, a portion of the air will pass through the hot deck and the rest will pass through the free deck (the proportion of each is based on the desired mixed-air temperature). The same types of controls were simulated for the three-deck multizone; however, an additional item (dual throttling range) was added to the controls. The dual throttling range allowed two temperature setpoints for the space temperature. This type of throttling range allows the heating system to control around a throttling range of 67 to 69°F (19 to 20°C) and the cooling to control around a throttling range of 77 to 79°F (25 to 26°C); there is no heating or cooling for space temperatures between 69 and 77°F (20 and 25°C).

In addition, a two-pipe fan/coil, a four-pipe fan/coil, and a variable air volume (VAV) system with perimeter heating were also simulated. The two-pipe fan/coil system was run with both single and dual throttling ranges, and with night and weekend setback. The two-pipe fan/coil system requires the heating and cooling to be turned off seasonally, since heating and cooling cannot be done simultaneously.

The four-pipe fan/coil and the VAV were modeled with heating and cooling capacity available the year around. Table 4 lists the systems and control strategies that were simulated.

Table 4

System and Control System Simulations

Parameter Changed	Barracks Building	Administration Building	Dental Clinic
Equipment			
Multizone		x	x
Three-deck multizone			x
Two-pipe fan/coil	x		x
Four-pipe fan/coil			x
VAV with perimeter heating			x
Controls (Space Temperature)			
Single throttling range			x
Single throttling range with night and weekend setback			x x
Dual throttling range	x	x	
Dual throttling range with night and weekend setback			x
Controls (Deck)			
Fixed set-point	x	x	x
Outside-air-controlled			x
Zone-controlled			x

3 RESULTS

This chapter describes the various BLAST program simulation results as the percentage difference in energy consumption caused by changing the test buildings' design. Data are tabulated so that a positive percentage indicates additional energy use and a negative percentage indicates a reduction in energy use. In each case, the energy consumption of heating and cooling systems is tabulated separately.

Table 5 shows the annual simulated heating and cooling loads in millions of Btus for the three building types and the five climatic locations. This table summarizes the total annual heating and cooling loads for the buildings and shows the relative ratios of heating and cooling in each building for each location. By referring to this table and to Table 1, the comparisons between heating load and heating degree days and cooling load and cooling degree days can be observed.

Insulation Levels

Table 6 shows the percentage difference various levels of wall and roof insulation thicknesses make in annual heating energy consumption for the barracks building in each of the five climatic locations simulated by the BLAST program.* This table shows that although the percentage difference in annual heating energy consumption is higher for warmer climates, the actual total amount of energy consumed is greater for colder climates. For example, adding 2 in. (101 mm) of polystyrene to walls saves 16 percent in Charleston and 14 percent in Washington, but the energy savings is only 42 MBtu in Charleston compared to 79 MBtu in Washington (0.16 x 264 = 42 MBtu and 0.14 x 566 = 79 MBtu, respectively). Table 6 shows that the design level of insulation in the roof of the building ("U" value = 0.058 Btu/^{O}F sq ft-hr [0.33 W/^{O}K-m^{2}]) is sufficient, since additional roof insulation does not provide a significant savings in annual heating energy consumption. However, the level of wall insulation can be improved; i.e., by supplying 2 in. (101 mm) of polystyrene in the wall air space (an overall wall "U" value of 0.07 Btu/^{O}F-ft^{2}-hr [0.4 W/^{O}K-m^{2}] instead of 0.24 Btu/^{O}F-ft^{2}-hr [1.36 W/^{O}K-m^{2}), a reduction of about 15 percent can be achieved. In the three-story barracks building, the effect of wall insulation is more important than roof insulation because the wall area containing insulation (excluding windows and doors) is almost double that of the roof area -- 6600 sq ft (594 m^{2}) vs 3400 sq ft (306 m^{2}).

Table 7 shows the percent difference various levels of insulation make in the barracks building's annual cooling energy consumption. Filling the hollow cores of the concrete block with insulation, as shown on the as-built plans, has a relatively small effect on cooling energy consumption, whereas the effect of the as-built roof insulation is more significant. As in the heating mode, additional roof insulation has a negligible effect, while adding wall insulation reduces total cooling energy consumption by 5 percent. Both Tables 6 and 7 show that insulation levels have a much greater effect on heating consumption than on cooling consumption; this is caused by the fact that there is a much smaller temperature differential between outdoor and indoor temperatures during the cooling season.

Table 7 shows there was an increase in cooling energy use when insulation was added to the walls during the weather year used in the Los Angeles simulation. This indicates the internal gain of the space is not allowed to escape through the walls as rapidly when the insulation level is increased, thus requiring additional cooling. However, the total energy consumption (heating and cooling) is lower when the insulation is added (Tables 6 and 7).

Table 8 shows the percent difference insulation made in heating energy consumption for the administration building simulation. The results are basically the same as those for the barracks building, except that adding roof insulation has a more significant effect, since this is a single-story building with an exterior wall area that is only one-third the area of the roof. However, adding wall insulation to a space previously containing air is more significant than adding roof insulation and can produce an energy savings of about 15 percent. Also, as shown for the barracks building, the original roof insulation (2 in. [51 mm]) saves more energy that does the filled core of the concrete blocks. It therefore appears that roof insulation thickness is more nearly optimized than wall insulation. However, care

* Table 2 gives wall, roof, and overall "U" values for each variation of insulation level and should be consulted when comparing energy consumption for different levels of insulation.

Table 5

Annual Heating and Cooling Loads for As-Built Structures (Btus x 10^6) (Metric Conversion Factor: 1 Btu = 1.055 kJ)

Description	Washington, DC	Charleston, SC	Los Angeles, CA	Columbia, MO	Fort Worth, TX
Barracks					
Heating	566	265	88	699	262
Cooling	204	318	93	191	383
Administration					
Heating	1236	635	317	1467	645
Cooling	107	142	172	117	220
Dental Clinic					
Heating	685	558	366	733	526
Cooling	669	690	508	571	811

Table 6

Barracks Building Heating Energy Consumption Differences Due To Varied Insulation (Percent From Basic Building) (Metric Conversion Factors: 1 in. = 25.4 mm; 1 Btu = 1.055 kJ)

Description	Washington, DC	Charleston, SC	Los Angeles, CA	Columbia, MO	Fort Worth, TX
Basic building (Btus x 10^6)	566	264	88	699	262
1. Remove insulation in concrete block wall cores	+6%	+7%	+14%	+7%	+8%
2. Remove 2 in. of insulation from roof	+9%	+11%	+23%	+9%	+11%
3. Remove both as-built wall and roof insulation	+15%	+17%	+36%	+15%	+19%
4. Add 2 in. of polystyrene to walls	-14%	-16%	-30%	-13%	-17%
5. Add 4 in. of fiberglass to roof	-1%	-2%	-3%	-1%	-1%
6. Add 2 in. of poly styrene to walls and 4 in. of fiberglass to roof	-15%	-17%	-33%	-14%	-18%

Table 7

Barracks Building Cooling Energy Consumption
Differences Due To Varied Insulation (Percent From Basic Building)
(Metric Conversion Factors: 1 in. = 25.4 mm; 1 Btu = 1.055 kJ)

Description	Washington, DC	Charleston, SC	Los Angeles, CA	Columbia, MO	Fort Worth, TX
Basic Building (Btus x 10^6)	204	318	93	191	383
1. Remove insulation in concrete block wall cores	+2%	+2%	+3%	+1%	+2%
2. Remove 2 in. of insulation from roof	+8%	+6%	+11%	+4%	+6%
3. Remove both as-built wall and roof insulation	+10%	+7%	+5%	+6%	+8%
4. Add 2 in. of polystyrene to walls	-5%	-3%	+11%	-6%	-5%
5. Add 4 in. of fiber-glass to roof	-1%	-1%	-2%	-4%	-1%
6. Add 2 in. of poly-styrene to walls and 4 in. of fiberglass to roof	-6%	-4%	+9%	-10%	-6%

Table 8

Administration Building Heating Energy Consumption
Differences Due To Varied Insulation (Percent From Basic Building)
(Metric Conversion Factors: 1 in. = 25.4 mm; 1 Btu = 1.055 kJ)

Description	Washington, DC	Charleston, SC	Los Angeles, CA	Columbia, MO	Fort Worth, TX
Basic Building (Btus x 10^6)	1236	635	317	1467	645
1. Remove insulation in concrete block wall cores	+4%	+4%	+5%	+3%	+4%
2. Remove 2 in. of insulation from roof	+14%	+15%	+22%	+12%	+16%
3. Remove both as-built wall and roof insulation	+17%	+18%	+27%	+15%	+19%
4. Add 2 in. of polystyrene to walls	-7%	-8%	-13%	-7%	-8%
5. Add 4 in. of fiberglass to roof	-4%	-5%	-7%	-4%	-5%
6. Add 2 in. of poly-styrene to walls and 4 in. of fiberglass to roof	-12%	-13%	-20%	-11%	-13%

must be taken when comparing percentages, since for the same amount of insulation added, a warmer climate has a greater percentage difference in energy consumption, but a lower amount of energy saved.

Table 9 shows the percentage difference varied insulation levels make in annual cooling energy use in the administration building. For this single-story building, the cooling load resulting from heat transfer through the roof is much more significant than for walls. The BLAST simulation indicated neither removal of insulation from the concrete block cores nor addition of wall insulation significantly affected cooling energy consumption.

Table 10 shows the percentage difference from the basic as-built clinic caused by varying insulation levels. Since this building has a crawl space, the simulation varied both roof and floor insulation. For this single-story building, roof insulation effects a significant energy savings, e.g., 18 percent in Fort Worth, TX and 12 percent in Washington, DC. The simulation runs made with the floor insulation removed increased the annual heating load 2 and 4 percent in Fort Worth and Washington, respectively; adding insulation caused a slightly lower heating energy use.

One additional item observed was the effect of the 2-ft (0.6-m) overhang around the clinic. Simulation runs showed that removing the overhang had an insignificant effect on heating energy use.

Table 11 shows the cooling energy consumption differences made by varying the clinic's floor and roof insulation and removing its overhang. These results parallel the heating consumption effects; i.e., insulation levels have less effect on cooling loads than on heating loads. The overhang in this building has an insignificant effect on cooling consumption; the same effects are noted for crawl space insulation.

Orientation

Table 12 shows the differences various building orientations make in annual heating and cooling consumption. For the BLAST simulation's basic run, each building was originally modeled in the orientation recommended in the *DOD Construction Criteria Manual*; later each building was rotated 45 and 90 degrees from the original. The table shows that building orientation does not significantly affect annual heating energy consumption for these buildings, but more prominently affects annual cooling energy consumption. This is particularly true in the barracks building, mainly because the three-story building has a larger amount of window and exposed wall area. The results also confirm that the effect on energy consumption caused by orientation is more important for multi-story buildings.

Window Size and Type

Table 13 shows the BLAST-simulated heating energy consumption differences caused by varying window area and type. When the simulations were run without windows, the space normally occupied by the glass was replaced with as-built wall construction materials. The effect of the window area is not linear in the heating mode; i.e., doubling the window area does not give the same percentage difference as eliminating windows. Also, using a double-glazed window is nearly as effective as reducing window area and can provide at least a 10 percent energy savings in the barracks building and 5 percent energy savings in the administration building for the locations studied.

Table 14 shows the BLAST simulated cooling energy consumption difference caused by varying window area and type. Although the percentage differences are much greater for the cooling loads, the amount of energy difference (percentage times basic building use) is nearly the same. The effect of window area on cooling energy consumption appears to be more linear than for heating. This is because the effect of overall wall "U" values (which change when window size changes) is smaller in the cooling mode (Tables 7 and 9). Table 14 also shows that double-pane glass has a relatively small effect on total annual cooling energy use.

Table 9

Administration Building Cooling Energy Consumption Differences Due To Varied Insulation (Percent From Basic Building) (Metric Conversion Factors: 1 in. = 25.4 mm; 1 Btu = 1.055 kJ)

Description	Washington, DC	Charleston, SC	Los Angeles, CA	Columbia, MO	Fort Worth, TX
Basic Building (Btus x 10^6)	107	142	17.2	117	220
1. Remove insulation in concrete block wall cores	+1%	+1%	-8%	+1%	+1%
2. Remove 2 in. of insulation from roof	+21%	+17%	+40%	+25%	+16%
3. Remove both as-built wall and roof insulation	+22%	+18%	+31%	+26%	+17%
4. Add 2 in. of polystyrene to walls	-3%	-1%	+16%	-3%	-4%
5. Add 4 in. of fiberglass to roof	-8%	-6%	-15%	-9%	-5%
6. Add 2 in. of polystyrene to walls and 4 in. of fiberglass to roof	-11%	-8%	+3%	-13%	-9%

Table 10

Dental Clinic Heating Energy Consumption Differences Due To Varied Insulation (Percent From Basic Building) (Metric Conversion Factors: 1 in. = 25.4 mm; 1 ft = .305 m; 1 Btu = 1.055 kJ)

Description	Washington, DC	Fort Worth, TX
Basic Building (Btus x 10^6)	685	526
1. Remove 3 in. of insulation from roof	+12%	+18%
2. Remove 1 in. of insulation from floor	+4%	+2%
3. Remove 2 ft of overhang	0%	0%
4. Add 2 in. of fiberglass to floor	0%	-1%

Table 11

Dental Clinic Cooling Energy Consumption Differences Due To Varied Insulation (Percent From Basic Building) (Metric Conversion Factors: 1 in. = 25.4 mm; 1 ft = .305 m; 1 Btu = 1.055 kJ)

Description	Washington, DC	Fort Worth, TX
Basic Building (Btus x 10^6)	669	811
1. Remove 3 in. of insulation from roof	+1%	+2%
2. Remove 1 in. of insulation from floor	+1%	+1%
3. Remove 2 ft of overhang	0%	0%
4. Add 2 in. of fiberglass to floor	-1	-1

Table 12

Heating and Cooling Energy Consumption Differences Due To Building Orientation (Percent From Basic Building) (Metric Conversion Factor: 1 Btu = 1.055 kJ)

Description	Washington, DC	Charleston, SC	Los Angeles, CA	Columbia, MO	Fort Worth, TX
1. Barracks -- heating basic building (Btus x 10^6)	566	264	88	699	262
45% rotation	-2%	-4%	-8%	-2%	-3%
90% rotation	-1%	-2%	-7%	-1%	-2%
2. Administration -- Heating Basic building (Btus x 10^6)	1236	635	317	1467	645
45% rotation	+0.3%	+0.3%	-1%	+1%	0%
90% rotation	+1%	+1%	+1%	+2%	+1%
3. Barracks -- cooling basic building (Btus x 10^6)	204	318	93	191	383
45% rotation	+8%	+7%	+20%	+6%	+6%
90% rotation	+17%	+12%	+42%	+16%	+11%
4. Administration -- cooling basic building (Btus x 10^6)	107	142	172	117	220
45^o rotation	+2%	+3%	+15%	+6%	+1%
90^o rotation	+2%	+3%	+21%	+7%	+2%

Table 13

Heating Energy Consumption Differences
Due To Window Area and Type (Percent From Basic Building)
(Metric Conversion Factor: 1 Btu = 1.055 kJ)

Description	Washington, DC	Charleston, SC	Los Angeles, CA	Columbia, MO	Fort Worth, TX
1. Barracks -- basic building (Btus x 10^6)	566	264	88	699	262
No windows	-13%	-14%	-23%	-15%	-25%
Double window area	+7%	+8%	+17%	+9%	+15%
Double-pane glass	-11%	-14%	-28%	-10%	-15%
2. Administration -- basic building (Btus x 10^6)	1236	635	317	1467	645
No windows	-6%	-6%	-12%	-5%	-7%
Double window area	+1%	+1%	0%	+0.5%	+1%
Double-pane glass	-5%	-6%	-9%	-5%	-6%

Table 14

Cooling Energy Consumption Differences
Due To Window Area and Type (Percent From Basic Building)
(Metric Conversion Factor: 1 Btu - 1.055 kJ)

Description	Washington, DC	Charleston, SC	Los Angeles, CA	Columbia, MO	Fort Worth, TX
1. Barracks -- basic building (Btus x 10^6)	204	318	93	191	383
No windows	-28%	-25%	-23%	-29%	-26%
Double window area	+27%	+21%	+38%	+22%	+22%
Double-pane glass	-0%	-1%	-12%	-2%	-2%
2. Administration -- basic building (Btus x 10^6)	107	142	172	117	220
No windows	-19%	-11%	+1%	-21%	-10%
Double window area	+17%	+13%	28%	+21%	+9%
Double-pane glass	-2%	+1%	+28%	-3%	-3%

Infiltration

Table 15 shows the simulated results of varying the infiltration rates for the barracks and administration buildings. The assumed as-built infiltration rates were 3000 and 3860 cu ft/min (60 and 77 m^3/min), respectively, for the barracks and administration buildings. In the heating mode, infiltration or forced outside air ventilation is a very significant part of the annual heating load. In the cooling mode, infiltration does not have as great an effect because of the lower temperature differential between outside air and the conditioned space temperature. However, it can be seen that infiltration (in the cooling mode) is more significant in the warmer climates (i.e, Charleston and Fort Worth) since the outdoor temperatures are higher, and the temperature differential is therefore greater.

System Controls

System simulations were done for the dental clinic buildings using typical weather year tapes from Washington and Fort Worth. Table 16 shows the simulated heating and cooling consumption of various control strategies for the clinic's multizone air distribution system. The first simulation run was made for a system that had continous operation, controlled the space temperature at a single throttling range (73 to 77°F [23 to 25°C]) and had fixed set-point control on the hot and cold decks. This type of control system allows simultaneous heating and cooling of air to achieve a desired mixed-air temperature to satisfy the building load. This system is always either heating or cooling the air, or both, since all the air must pass over the hot or cold deck. This type of control strategy was used for reference only since it is no longer considered a practical way of heating and cooling buildings.

The second run was made with a multizone system as it might be installed in a building incorporating the control strategy recommended in the *DOD Construction Criteria Manual.* This system, which incorporates night and weekend setback, is much more energy-conservative than continuous operation. In addition, the heating and cooling consumption difference between various hot- and cold-deck controls given in Table 16 indicates that outside-air-controlled decks are the most energy-conservative. This is also the recommended method for hot- and cold-deck control given in the *DOD Construction Criteria Manual.* Table 16 also shows that a temperature economy cycle slightly increases the heating load, but substantially reduces the cooling load.

Table 17 gives the simulated results of different control strategies for a three-deck multizone system. As might be expected, the three-deck multizone is more efficient than a standard multizone, since the air is not heated and cooled simultaneously. The variations in control strategies for the three-deck multizone are similar to the multizone system, where the outside-air-controlled decks are the most efficient. For the three-deck multizone system, the sum of the annual heating and cooling loads for a system using a temperature economy cycle is higher than without the economy cycle. Table 18 shows the effects of system types on annual heating, cooling, and fan system energy consumption; the same types of control strategies, where applicable, were used for these comparisons. When using a single throttling range, the most efficient system is a two-pipe fan/coil system. The second best system is a VAV system. However, during the simulation of the two-pipe system, the heating and cooling coils were turned off seasonally, since a two-pipe system can only heat or cool. This control strategy could allow the building zone temperature to exceed the thermostat set point if unseasonably hot weather is encountered when the cooling is off. Therefore, a two-pipe fan/coil system may not be appropriate for a building requiring more precise control (such as dental clinic) or for buildings that have interior zones requiring cooling all year. The VAV system uses slightly less energy at the Washington location if the total load is considered, because of a higher demand for heating, and slightly more energy at Fort Worth, where the cooling load dominates.

Table 18 also shows that at least a 50 percent reduction in energy usage can be achieved by using night and weekend setback and dual throttling ranges. When using night and weekend setback with dual throttling ranges, the two-pipe fan/coil system has the lowest annual energy consumption; both the VAV system and the four-pipe fan/coil system show a slightly higher annual consumption. It should be noted that the VAV system reduces the heating energy requirement by about 50 percent over either the two- or four-pipe fan/coil. Also, the fan power consumption is approximately 25 percent higher for the VAV system over the two- and four-pipe system, but at least 50 percent lower than that for the multizone system.

Table 15

Heating and Cooling Energy Consumption Differences
Due To Infiltration and Ventilation (Percent From Basic Building)
(Metric Conversion Factor: 1 Btu = 1.055 kJ; 1 CFM = 0.028m^3)

Description	Washington, DC	Charleston, SC	Los Angeles, CA	Columbia, MO	Fort Worth, TX
1. Barracks -- Heating basic building (3000 CFM) (Btus x 10^6)	566	264	88	699	262
Zero infiltration	-60%	-67%	-84%	-63%	-70%
Double infiltration	+61%	+72%	+118%	+65%	+75%
2. Administration -- heating basic building (3860 CFM) (Btus x 10^6)	1236	635	317	1467	645
Zero infiltration	-37%	-40%	-78%	-38%	-71%
Double infiltration	+37%	+72%	+104%	+38%	+73%
3. Barracks -- cooling basic building (3000 CFM) (Btus x 10^6)	204	318	93	191	383
Zero infiltration	+3%	-17%	+63%	+0.5%	-23%
Double infiltration	+8%	+8%	-32%	+4%	+18%
4. Administration -- cooling basic building (3860 CFM) (Btus x 10^6)	107	142	172	117	220
Zero infiltration	-3%	-11%	+63%	-3%	-21%
Double infiltration	+7%	+13%	-31%	+7%	+23%

Table 16

Effects of Control Strategies for Multizone System -- Dental Clinic ($Btus \times 10^6$) (Metric Conversion Factor: 1 Btu = 1.055 kJ)

Multizone System	Washington, DC Heating	Washington, DC Cooling	Fort Worth, TX Heating	Fort Worth, TX Cooling
1. Fixed set-point decks, continuous operation, single throttling range.	1620	1419	1527	1820
2. Outside-air-controlled deck, intermittent operation, single throttling range.	1124	880	1014	1231
3. Fixed set-point decks, intermittent operation, night and weekend setback with single throttling range.	685	669	526	811
4. Zone-controlled decks, intermittent; night and weekend setback with single throttling range.	443	423	312	594
5. Outside-air-controlled decks, intermittent; night and weekend setback with single throttling range.	410	369	296	540
6. Same as No. 5, except with temperature economy cycle.	441	285	313	426

Table 17

Effects of Control Strategies for Three-Deck Multizone System -- Dental Clinic ($Btus \times 10^6$) (Metric Conversion Factor: 1 Btu = 1.055 kJ)

Three-Deck Multizone	Washington, DC Heating	Washington, DC Cooling	Fort Worth, TX Heating	Fort Worth, TX Cooling
1. Fixed decks, continuous, single-throttling range	546	360	337	664
2. Same as No. 1, except night and weekend setback with dual throttling range	329	232	283	438
3. Same as No. 2, except intermittent	240	212	113	380
4. Same as No. 3, except OSA-controlled hot and cold decks	240	188	113	345
5. Same as No. 4, except with temperature economy cycle	344	138	186	304

Table 18

Effects of System Types on Energy Consumption -- Dental Clinic (Btus x 10^6) (Metric Conversion Factor: 1 Btu = 1.055 kJ)

	Washington, DC			Fort Worth, TX		
Description	Heating	Cooling	Fan Consumption	Heating	Cooling	Fan Consumption
Multizone (with fixed set-point decks, continuous operation, and single-throttling range)	1620	1419	98.5	1527	1820	72.8
Three-deck multizone (as above)	546	360	82.6	337	664	107
Two-pipe fancoil (as above)	550	252	31.7	297	493	31.7
VAV (as above)	328	438	40.7	212	623	44.8
Multizone (with fixed set points, intermittent, night and weekend setback with single throttling range	685	669	53.4	526	811	47.3
Three-deck multizone (same as above except dual throttling range)	240	212	53.2	113	380	47.0
Two-pipe fancoil (same as three-deck multizone)	199	155	14.3	118	298	13.5
Four-pipe fancoil (same as three-deck multizone)	203	179	14.3	132	331	13.5
VAV (same as three-deck multizone)	96	254	22.1	53	383	20.4

4 CONCLUSIONS

1. BLAST simulations of three typical Army buildings indicate that no single building variable will achieve an absolute across-the-board energy reduction. The reductions attainable for a given conservation option vary considerably from building to building and are greatly affected by the climatic region. Thus, energy reduction in new and existing buildings must be examined individually for each building and location.

2. Of all design considerations, mechanical system type has the greatest impact on energy consumption. For example, the dental clinic would consume 50 percent less energy if the multizone system were replaced with either a two-pipe fan/coil or a VAV system. This savings cannot be considered available for all buildings, since many Army buildings already use energy-efficient systems. For example, the energy consumption for the barracks building (which uses a two-pipe fan/coil system) cannot be significantly improved.

3. The most energy-conservative control strategy for multizone and three-deck multizone systems uses night and weekend setback, intermittent fan operation, and controls the hot and cold decks by outside air temperature.

4. Additional wall insulation significantly affects annual heating energy consumption in the barracks and the administration building. A minimum of 14 and 7 percent in the barracks and administration building, respectively, can be saved in annual heating consumption by adding insulation to wall air spaces.

5. By using double-pane windows, minimum savings of 10 and 5 percent for the barracks and administration buildings, respectively, can be realized in annual heating consumption.

6. Infiltration and ventilation can contribute up to 60 percent of the heating energy use in buildings. Substantial savings in heating energy consumption can be achieved by minimizing infiltration and outside air intake.

APPENDIX:

GENERAL DESCRIPTION OF THE BLAST COMPUTER PROGRAM

This appendix briefly describes the BLAST computer program used in this study to determine annual heating and cooling consumption for three typical Army buildings.

General

The BLAST program is a comprehensive set of subprograms for predicting energy consumption and energy systems performance and cost in buildings. There are three major subprograms (see Figure A1):

1. The Space Load Predicting Subprogram computes hourly space loads in a building or zone based on user input and weather data.

2. The Air Distribution System Simulation Subprogram uses the computed space loads, weather data, and user inputs describing the building air-handling system to calculate hot water, steam, gas, chilled water, and electric demands.

3. The Central Plant Simulation Subprogram uses weather data, results of air distribution system simulation, and user input describing the central plant to simulate boilers, chillers, onsite power generating equipment and solar energy systems, and computes monthy and annual fuel and electrical power consumption.

Apart from its comprehensiveness, the BLAST program differs in four key respects from similar programs used in the past.

1. The BLAST program uses extremely rigorous and detailed algorithms to compute loads, simulate fan systems, and simulate boiler and chiller plants.

2. The program has its own user-oriented input language and is accompanied by a library which contains the properties of all materials, wall, roof, and floor sections listed in the ASHRAE *Handbook of Fundamentals.*[1]

3. The program execution time is brief enough to allow many alternatives to be studied economically.

4. The program is not proprietary and is, therefore, open to inspection by its users and those who rely on its results.

The BLAST Input Language and Library

The BLAST program uses an unformatted, English-like input language which permits rapid input preparation. Error detection and some automatic correction make input data debugging easy. In addition, the English-like style permits rapid inspection and easy interpretation of user-supplied input.

Part of the BLAST program is the BLAST program library. The library is simply a file in which data (numbers) are stored under convenient names. It is divided into 10 subsets:

1. The Schedule Subset contains 24-hour profiles and specifications for using these profiles for each day of the week, weekends, and holidays. This subset is used when occupancy, lighting, equipment usage, and infiltration are described.

2. The Location Subset contains latitude, longitude, and time zone data for named locations.

3. The Design Day Subset contains design weather data for named design days.

4. The Control Subset contains space temperature control strategies for named control schedules.

5. The Material Subset contains the thermodynamic and optical properties of typical building materials.

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[1] *Handbook of Fundamentals* (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 1977).

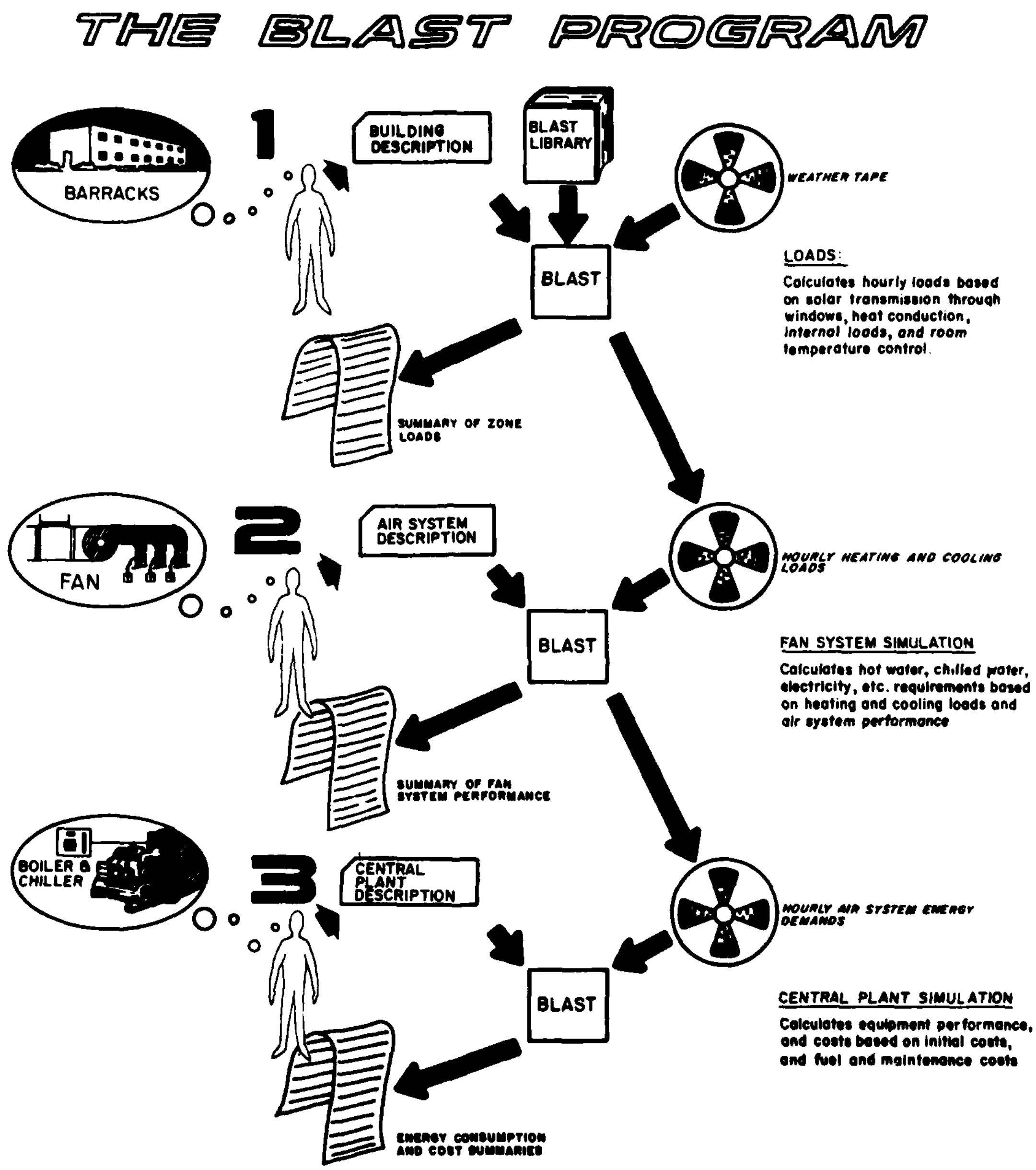

Figure A1. The BLAST program.

6. The Wall Subset contains typical wall section descriptions composed of materials from the library's materials subset.

7. The Roof Subset contains typical roof and ceiling sections composed of materials from the materials subset.

8. The Floor Subset contains typical floor sections composed of materials from the materials subset.

9. The Door Subset contains typical door sections composed of materials from the materials subset.

10. The Window Subset contains typical window sections comprised of glass, air spaces, interior shades and drapes from the materials subset.

In addition to selected schedules and control strategies, all materials, wall, roof, and floor sections found in the 1977 ASHRAE *Handbook of Fundamentals* are in the BLAST library; entry names are keyed to the tables in the ASHRAE Handbook. Therefore, when preparing a building description for the BLAST program, it is not necessary to input scores of numbers. Instead, short names -- which automatically select appropriate data from the library -- can be used to generate the information necessary for the BLAST program calculations.

Even though the BLAST program library is comprehensive, it may not contain all the materials, schedules, wall, roof, and floor sections, and control strategies required by the user. Consequently, the BLAST program language provides the user with the capability to add, delete, modify, or temporarily define entries in any of the library's subsets, or print the contents of the entire library (alphabetically and by subset).

In addition to library data, the BLAST input language provides for the use of default equipment performance and fan system data. This permits generic systems to be investigated easily and rapidly. It also allows the user to change only those variables for which defaults are inappropriate.

The Loads Predicting Subprogram

The heart of the space loads prediction subprogram is the room heat balance. For each hour simulated, BLAST performs a complete radiant, convective, and conductive heat balance for each surface of each zone described and a heat balance on the room air. This heat balance includes transmission loads, solar loads, internal heat gains, infiltration loads, and the temperature control strategy used to maintain the space temperature. Many of the important features of the loads predicting subprogram are summarized below:

1. Calculates response factors and conduction transfer functions for all zone surfaces. (This permits the careful and complete analysis of transient heat conduction through walls and of heat storage in rooms.)

2. Calculates the shaded and sunlit area for all exterior surfaces shaded by attached or detached shadow-casting surfaces (wings, overhangs, or other buildings). Also, the shading of windows caused by reveals is fully accounted for.

3. Exactly calculates the solar flux transmitted through single- and multipane windows with or without interior shades using either basic optical principles or "shading coeffients" specified by the user.

4. Accounts for the effects of both inside surface solar and infrared absorptivities and outside surface solar absorptivities.

5. Uses approximate shape factors to calculate radiant heat transfer between zone surfaces as part of the room heat balance. Also calculates the radiant interchange between exterior surfaces (i.e., walls, roofs, windows) and the earth and sky.

6. Accounts for the effecs of surface roughness and hourly variations in windspeed on outside wall convective heat transfer coefficients (air film resistance).

7. Adjusts the inside surface convective heat transfer coefficient (air film resistance) for ceilings, roofs, and floors based on whether the surfaces are hotter or colder than the room air.

8. Accounts for temperature differences between a zone and an attic or crawl space by actually simulating the attic and/or crawl space.

9. Includes approximate methods for the calculation of heat flow between zones of differing temperature.

10. Allows arbitrary (user-specified) room temperature control strategies. (Different control strategies can be specified for different hours during the day and different days during the week.)

11. Appropriately allocates radiant, convective, and latent fractions of the heat from people, lights, and equipment, and allows these internal gains to be scheduled differently for each hour of the day and each day of the week.

12. Simulates the radiant and convective effects of outside air-controlled baseboard heating.

13. Accounts for the effects of windspeed, temperature, and time of day on zone infiltration.

14. Allows surfaces bounding a zone to be of arbitrary shape, three- and four-sided, and at any tilt or azimuth.

15. At the discretion of the user, allows calculated loads for each zone to be saved on tape or disk for future use in examining many alternate fan system configurations (without recalculating space loads).

16. Simulates as many as 100 zones at one time (many more than are usually required).

The Fan System Simulation Subprogram

Once zone loads are calculated, they must be translated into hot water, chilled water, and electrical demands on a central plant or utility system. This is done by using basic heat and mass balance principles in the system simulation subprogram of BLAST. The major types of air distribution systems that BLAST can analyze are:

1. Multizone and dual duct systems
2. Three-deck multizone systems
3. Single-zone fan systems with subzone reheat
4. Unit ventilators with or without heating coils
5. Two-pipe fan/coil systems
6. Four-pipe fan/coil systems
7. VAV fan systems with optional reheat or thermostatically controlled baseboard heat
8. Constant volume terminal reheat systems
9. Dual duct VAV systems
10. Packaged direct-expansion systems
11. Single-zone drawthrough systems

In addition, built-up direct-expansion cooling can be specified to serve the fan systems listed above, or chilled water can be the cooling source. Air-to-air heat recovery is also possible on most of the systems listed above. Default values are supplied for most of the pertinent fan system variables. All defaults can, however, be overridden by the user. Many combinations of mixed- and delivery-air control strategies are available for most of the air distribution systems.

The fan system simulation subprogram is unusually flexible and precise in its analysis of fan system performance. This subprogram includes the following significant features:

1. The user may adjust both the full-load efficiency and total fan pressure for supply, return, and exhaust fan as well as the part-load performance characteristics of the supply and return fans.

2. Both cold and hot decks can be controlled (a) at a fixed temperature set point, (b) at a temperature varied with outdoor air temperature, or (c) on the basis of the zone requiring the most heating or cooling.

3. The user-specified or the default-throttling range of the cold and hot deck controllers is fully accounted for.

4. Three different economy cycles can be used for most fan systems; the mixed-air temperature may be fixed or floating depending on the user specification.

5. Minimum and maximum outdoor air quantities can be scheduled for each hour of the weekday or weekend.

6. Various preheat coil configurations can be simulated.

7. Minimum and maximum outdoor air quantities can be specified. Maximum total fan volumes may be specified for VAV systems. (The VAV maximum and the maximum outdoor air quantity can be less than the sum of the air distributed to all zones.)

8. Humidifiers can be specified for most systems.

9. Fan, heating coil, preheat coil, cooling coil, and heat recovery operation can be scheduled on a daily and seasonal basis.

10. Users may simulate any cooling coil by specifying cooling coil design parameters consisting of typical catalog data for one coil operating point.

11. At the discretion of the user, the results of fan system simulations may be saved on tape or disk for future use in examining many alternate central plant configurations (without repeating the fan system simulations).

12. BLAST can simulate as many as 100 separate systems at one time (many more than are usually required).

The Central Plant Simulation Subprogram

Once the hot water, chilled water, and electrical demands of the building fan system are known, the central plant must be simulated to determine the building's final purchased electrical power and/or fuel consumption. The central plant subprogram of BLAST can simulate any thermodynamically feasible system consisting of any or all of the following central plan components:

1. Boilers
2. Centrifugal or reciprocating chillers
3. Absorption chillers (one and two stages)
4. Double-bundle chillers
5. Heat pumps (with or without solar assist)
6. Solar collectors and storage tank systems
7. Hot thermal storage
8. Cold thermal storage
9. Cooling towers
10. Diesel engine generators
11. Gas turbine generators
12. Steam turbine generators
13. Heat recovery from generator prime movers
14. Utility company power.

Generic data for each component model are present in BLAST, but the user may vary one or more sets of equipment performance coefficients to simulate a particular manufacturer's product.

Some of the principal features of the central plant simulation program are:

1. Accounts for the effects of ambient temperature, chilled and hot water temperature, and other operating variables on plant performance and equipment capacity.

2. Accounts for the change in equipment Coefficiency of Performance (COP) or efficiency resulting from part-load operation.

3. Allows default equipment assignment strategies to be overridden, thereby permitting the user to select the operating strategy of his/her choice.

4. Allows the user to change equipment performance parameters to permit the exact modeling of available equipment.

5. Allows detailed energy accounting which permits accurate costing of energy, particularly of puchased electricity which may have complicated block rate schedules.

6. Tabulates equipment-use statistics (hours of operation and average part-load ratio for each plant component) as well as energy consumption data, thereby permitting BLAST output to be used as the basis for equipment selection.

7. Simulates as many as 100 central plants in one run.

Life-Cycle Costing

The last step in the BLAST central plant subprogram is the calculation of life-cycle costs using present worth life-cycle costing techniques. User inputs include building construction and operating costs (excluding energy), fan system construction and maintenance costs, and user-supplied and default capital and maintenance costs for plant components. In addition, users may select appropriate fuel cost adjustment factors and discount and inflation rates.

Applications

BLAST can be applied to a wide range of projects. For example:

1. BLAST can be used for new design or retrofit projects and can simulate buildings and energy systems of almost any type and size.

2. In addition to simulating the annual performance of buildings and their energy systems, BLAST can perform peak load (design day) calculations necessary for both heating and cooling coil selection and air distribution system design.

3. BLAST can evaluate building and energy system designs to determine if they comply with design energy budgets.

4. BLAST's life-cycle costing capability can compare costs between alternate building and energy system designs.

5. BLAST can estimate annual performance, which is essential for the design of solar and total energy (cogeneration) systems.

6. Since repeated use of BLAST is inexpensive, it can be used to evaluate, modify, and re-evaluate alternate designs on the basis of annual energy consumption and cost. In this way, efficient designs can be separated from the inefficient; proper equipment type, size, and control can also be determined. Near-optimal designs for any new or retrofit project can be developed using this approach.

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Windingland, Larry M.
Parametric analysis of energy consumption in Army buildings by the Building Loads Analysis and System Thermodynamics (BLAST) computer program. -- Champaign, IL : Construction Engineering Research Laboratory ; Springfield, VA : available from NTIS, 1980.
36 p. (Technical report ; E-162)

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